# Review of forest vertical structure parameter inversion based on remote sensing technology

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**Abstract:** Forest vertical structure is the most complex of all vegetation parameters which describes the vertical distributing characteristic of vegetation community. The forest vertical structure not only affects the contribution of vegetation components for canopy reflectance, but also constrains the extraction accuracy of forest characteristic parameters. It also has significance influences on land surface process. With the development of remote sensing technology, forestry remote sensing developed from early forest classification mapping to quantitative retrieval of forest characteristics parameters. At present, the forest parameters that retrieved from remote sensing data include leaf area index, forest biomass, concentrations of chlorophyll and carbon storage. These parameters mainly describe the forest biochemical characteristics and horizontal structures. There are few researches on the forest vertical p arameters inversion. This paper firstly focuses on two parameters of Leaf Area Density (LAD) at different heights and vertical Canopy Height Profiles (CHP) which describes the forest vertical structure in remote sensing, and summarizes their extracting methods based on remote sensing technology. Secondly several vertical profiles of typical vegetation types are collected. Finally, i ssues in the forest vertical structure parameter extraction are discussed, and the new research directions in this area are suggested.

**Key words:** forest vertical structure, leaf area density, canopy height profile, InSAR, LiDAR

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## 1 INTRODUCTION

Forest ecosystem is often characterized as widely distributed, with complex structure and high species diversity. Besides, forest is the most perfect repository and biological gene pool in nature, and the storage and regulation library of water, carbon, nutrients and energy. Forest has an irreplaceable role in improving ecological environment and maintaining ecological balance (Pang, 2005).

Forestry remote sensing is an important field of remote sensing applications. In early 1970s, aerial remote sensing data were firstly used for forest mapping. In middle and late 1970s, high resolution aerial remote sensing technology promoted the i dentification and monitoring studies of forest classification (Li, 1990). At present, with the development of remote sensing technology, based on multispectral, hyperspectral, radar and laser radar remote sensing data, researchers carry out a wide range of monitoring and assessment researches of forest types and structural features. The optical or microwave remote sensing, and a ctive laser radar technology were used to monitor the growth states of forest (Pang, 2005). Forest parameters acquired from r emote sensing data include Leaf Area Index (LAI), biomass, concentration of canopy biochemistry components (such as chlorophyll, nitrogen and moisture content, carbon stocks), tree height, crown shape, forest type, canopy density and forest healthy status factors. These parameters mainly describe b iochemical and physical characteristics and horizontal structural features of forest.

The forest biochemical and physical parameters acquired from remote sensing mainly describe the vegetation distribution states and patterns in horizontal surface. Researches about vegetation vertical heterogeneity are not well known. The key factor causing inversion error of forest parameters from remote sensing data is the complicated vertical structure of vegetation. Therefore, efforts are seen on the extraction of forest vertical structure p arameters. Forest vertical structure represents the hierarchy of forest layer in vertical direction, the distribution manner of individual plants constituting a community in vertical space (Zheng,

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2008). Forest vertically hierarchy results from vegetation nature selection of sunlight, nutrients and water, and directly affects the vegetation growth and plant community succession process (Han & Li, 1999). Forest vertically hierarchy is important to improve the retrieving accuracy of forest biomass and LAI, and to study the forest succession, carbon cycle, primary productivity (De Wasseige & Defourny, 2002). Now, forest vertical structure p arameter extracting from remote sensing data has become a hotspot for forestry, ecological environment and remote sensing science researches (He, 2009; Tan, 2008).

## 2 FOREST VERTICAL STRUCTURE DISTRIBUTION CHARACTERISTICS AND EXPRESSION OF REMOTE SENSING PARAMETERS

### 2.1 Expression of forest vertical structure characteristics

Forest is a biome that is dominated by trees and other woody plants, and it constantly precedes material and energy e xchange with biosphere, water and land ecosystems. In vegetation communities, because different plants occupy different spaces, forest communities form a certain spatial structures. The forest spatial structures include vertical and horizontal structures (Sun, 2000). The horizontal structure refers to distribution states and patterns of plant communities on the ground, such as regular distributed grass in desert and clustered distributed shrub in forest. The vertical structure refers to vertical stratifications of community in space.

Forest vertical structure describes a phenomenon of surface plants organs (branches, leaves) vertically arranged in layers. It is associated with light usage. Because the canopy layer absorbs most of light radiation, the light intensity gradually decreases by tree trunks and foliage interception. Therefore, forest canopy forms tree canopy layer, understory layer, shrub layer, and herbaceous or moss plants composed of herb layer from top to bottom respectively (Chen, 1999) (Fig. 1(a)). Upper tree canopy layer is the mainly part of forest; it can fully make use of sunlight. Sometimes, only tenth of full sunlight can get through tree canopy layer and reach the next layer. Thus, the shrub and herb vegetation which can effectively make use of weak light is d istributing under the tree canopy. In the bottom of canopy, there are more shade-tolerant plants like mosses and lichens under the herb layer (Zhu, et al., 2004).

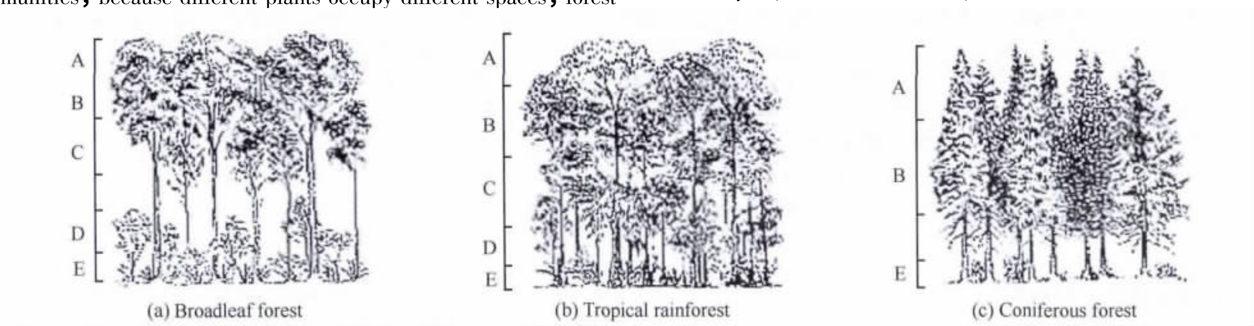


Fig. 1 Vertical structure distributions of three typical forest types (Chen, 1999)
(A: Upper layer of tree canopy; B: Lower layer of tree canopy; C: Understory layer; D: Shrub layer; E: Herb layer)

Vertical structure of forest community results from the a daption of plants to different ecological environment, and it s ignificantly improves the ability of plants to make use of environmental resources. Different forest types have different vertical structures. If a community has more superior conditions of h ydrology and climate, its vertical structures become more complex, and the mechanism of vegetation internal actions become more complicated. For example, the vertical structure of tropical rainforest is more complex than broad leave forest and coniferous forest (Fig. 1(b) and Fig. 1(c)).

### 2.2 Forest vertical structure parameters

In forestry, parameters which used to describe forest structure include tree height, basal area at breast height, canopy density, stand density, volume, and biomass (Zhao, et al., 2008). These parameters describe forest spatial distribution patterns and productivities. But the forest parameters extracted from remote sensing data focus on forest structure parameters. The forest structure parameters extracted from remote sensing data includes forest biophysical parameters (such as tree height and single tree crown contours, forest types, LAI and biomass, canopy density and stand density), forest biochemical parameters (such as chlorophyll content, carbon stocks), and forest healthy factors (Liu, e t al., 2009; Tan, et al., 2008; Xu, 2008; Yang, et al., 2010; Yang, et al., 2010; Zhao, et al., 2008). These parameters reflect the i nternal properties and structural characteristics of forest.

Among these forest structural parameters, the parameters which are used to express forest vertical stratification are few. This paper focuses on the parameters of describes forest vertical structure. In forestry, tree height is considered as the basis of d ividing different forest layers, and is one of the parameters that describes forest vertical structure. This parameter only provides tree height values, while does not reflect the growth state of trees in vertical. Accordingly, LAD curve which describes the distribution of leaf area at different height, and CHP parameter which describes the canopy spatial distribution in vertical are used to describe forests growth condition vertically based on remote sensing technology.

#### 2.2.1 Leaf area index

LAI is a dimensionless parameter, and it is one of the basic parameters that describing vegetation canopy structure. At first, LAI is defined as the total one-side area of leaves involved in photosynthesis process per unit ground surface area (Watson, 1947). This definition applies to flat broad leaves which the leaf area of front and back side is equal. As for the wrinkled, bent or rolled non-flat leaves, and the conifer needles which may be c ylindrical or close to hemi-cylindrical, this definition has great limitations.

Ross (1981) drew the outline of leaves to estimate LAI from field measurement. When measured the non-flat leaves or needle leaves, LAI was defined as the projected area of leaves (Ross, 1981; Chen & Black, 1992). Since then, many researchers defined LAI as the projected area of leaves per unit ground s urface area (Bolstad & Gower, 1990; Smith, 1991). But this d efinition has a main problem that is to how to choose the p rojection angle.

Chen and Black defined LAI as half the total leaf area per unit ground surface area (Chen & Black, 1991; Chen, et al., 1991). It is the most widely used definition at present. But this definition does not apply to non-flat leaves or coniferous leaves. Therefore, based on the concept of radiation intercepted by plant elements, Chen and Black defined LAI as half the total intercepting area per unit ground surface area for coniferous forest or non-flat leaves (Chen & Black, 1992). This definition not only reflects physical meaning of the radiation flux intercepted by leaf, but also has certain biological meaning.

### 2.2.2 Leaf area density

LAI is used to describe total leaf area of continuous vegetation canopy; it does not reflect the canopy leaf area changes with height. So, it is necessary to introduce a parameter that d escribes the leaf area differences within different vegetation layers vertically, Leaf Area Density (LAD). LAD defined as total one-sided leaf area which involved in photosynthesis process per unit canopy volume, at canopy height $z$ (Myneni, e t al., 1989; Weiss, et al., 2004). If the plants flourish in one layer, the LAD value of this layer is larger (Fig. 2). The sum of each layer's LAD value of whole canopy height $h$ is the canopy LAI. The relationship between LAD and LAI can be expressed as

$$\mathrm{LAI} = \int_0^h \mathrm{LAD}(z')\,\mathrm{d}z' \qquad (1)$$

LAD describes the leaf area distribution changes with height $z$, and it changes with species, growth stages, and environmental interferences. It is an important input parameter for ecological processes model.

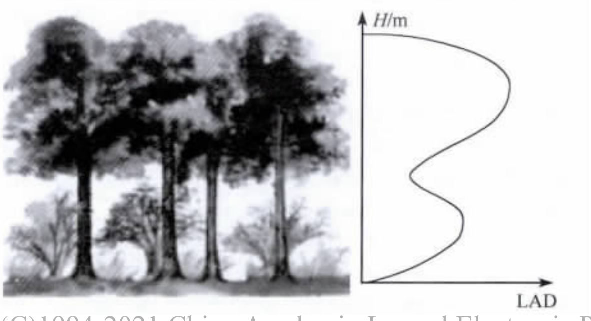


Fig. 2 Graph of the leaf area density distribution

### 2.2.3 Canopy height profile

Canopy Height Profile (CHP) is total surface area of all canopy components (including foliage and woody) and heights. In contrast, Foliage Height Profile (FHP) only describes the foliage surface area distribution changing with canopy height, from the ground to top of canopy (Lefsky, et al., 1999a). These two p arameters both describe the leaf growth d ensity of vegetation layers changes with the altitude, the only difference between them is the description of objects domain.

CHP is proposed under the context of LiDAR detection technology used to monitor forest vertical structure. The large spot LiDAR can completely record amplitude changes between the laser pulse initial and final echo signals, and the waveform is closely related to canopy vertical structure (Harding, et al., 2001). In dense vegetation, the intensity of laser echo signals is large (Fig. 3). Canopy vertical structures can be reconstracted from these signals. At present, the way of extracting forest vertical structural parameters from full waveform large spot L iDAR data is to convert the echoes into CHP curve.

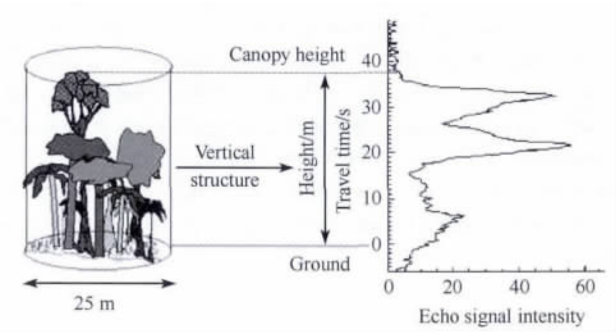


Fig. 3 Sketch map of large footprint LiDAR waveform form forest (Drake, et al., 2002)

## 3 EXTRACTION METHODS OF FOREST VERTICAL STRUCTURE PARAMETERS BASED ON REMOTE SENSING TECHNOLOGY

In forestry remote sensing, the parameters that describe forest vertical structural characteristics are LAD and CHP. The following part will summarize the extraction methods of LAD and CHP from remote sensing data.

### 3.1 Methods of LAD extracted from remote sensing data

The model inversion method of LAD parameters extracted from remote sensing data is based on statistical or physical models between the vegetation reflection and scattering of electromagnetic radiation signals and vegetation structure parameters. They use the electromagnetic signals to retrieve vegetation structure parameters. Leaves, branches and trunks in forest canopy are considered as scattering objects. The radar echo signals are generated from reflections or scatterings of these scattering bodies. The scattering density level depends on the orientation of vegetation scattering bodies, such as the vertical directional components of twigs and trunks.

The manner of radar polarization and interferometer have different response to various components of vegetation, in m icrowave remote sensing. Based on radar equation and existing statistical or physical models between correlation coefficients and vegetation structure parameters, we can use the radar echo signals to inverse vegetation structure parameters. Recently, studies of pine or northern forest LAD distribution extracted from polarimetric and interferometric radar echo signals are r eported (Treuhaft, et al., 1999, 2000, 2006, 2009).

LiDAR can actively obtain the three-dimensional coordinates information of objects. Small spot LiDAR point cloud data record the contact probability between pulse signal and vegetation components. Based on gap probability or leaves interception rate theory and statistical model between LiDAR echo signals and LAD, many researchers have successfully extracted LAD curve of single plant species or single type of vegetation from small spot LiDAR point cloud data.

### 3.1.1 Microwave extraction method

The polarization radar is sensitive to vegetation distribution and orientation, and interference radar is sensitive to vegetation spatial distribution (Treuhaft & Cloude, 1998). Therefore, based on the multi baseline and frequency interferometer′s amplitude and phase information (Treuhaft, et al., 2000) and the single baseline polarimetric interferometry radar information at different heights (Treuhaft, et al., 1999), the radar signals can be used to estimate f orest structure parameters and analyze its extinction characteristics. It is feasible to extract forest structural parameters based on microwave data.

The sixty-four dollar question of inversing vegetation vertical structures from InSAR data is to establish the relationship between coherent equation coefficients and vegetation vertical structure parameters. First, coherent equation can express quantitative relationship of vegetation body and surface components. Then, radar polarization interferometer echo signals are used to calculated vegetation structure parameters (Treuhaft & Cloude, 1998). Treuhaft, et al. (2006) used C-band InSAR data to obtain the least squares solutions among phase, correlation coefficients, extinction coefficient and relative density at six different baselines, and extracted the vegetation relative density profile. The simulation results are consistent with field measurements. Chen, et al. (2009) based on the local polarization interferometer coherence optimization algorithm using dual-baseline polarimetric i nterferometry data extracted vegetation vertical structure profiles. The error between simulation results and model simulation results is less than 0.6.

In addition, multi-baseline polarimetric InSAR technology can effectively identify the vegetation cover; it can be used to e stimate vegetation parameters and detect forest vertical profile characteristics (Pang, et al., 2010). Treuhaft and Chapman (2009) assumed the relatively LAD curve was following Gaussian distribution, and amended the expression of InSAR coherence equation. Using multi-baseline airborne of AirSAR C-band data, they directly computed the tropical rainforest LAD distribution with simulation accuracy of 17%—19% (Treuhaft, et al., 2009). The simulation accuracy is affected by the correlation coefficient calibration differences or the phase function error of radar interferometry signal.

Microwave remote sensing data can obtain vegetation vertical scale information, but the capability of obtaining forest vertical structure information from single sensor is limited. B ecause high spectral data is sensitive to vegetation optical characteristics, many scholars studied the methods of multiple sensors jointly inversed LAD curves. Treuhaft and Asner (2002) firstly used Radar and hyperspectral data jointly to retrieve LAD. A ssuming the relative density function is affected by Radar data while LAI is affected by hyperspectral data, they obtained the vegetation LAD curves and LAI values based on the relationship between radar equation and relative density function. The error between simulation results and measurement values is 1%—2%. But the major problem is that inversion method did not consider the dependence on other parameters on Radar and hyperspectral data. Therefore, this approach still needs further investigation (Treuhaft, et al., 2002).

Because the complex expression of interference radar equation, it needs to set up many auxiliary parameters and boundary conditions in solution process. This problem affects the accuracy of LAD extraction to some extent. Therefore, the method using microwave data extracted LAD has not been widely used.

### 3.1.2 LiDAR estimate method

Because LiDAR has a strong penetrating ability for forests, it has a significant advantage in forest parameters acquisition. The small spot LiDAR at a relatively small scale and it can get more point cloud data within the scope of single tree. So it can estimate parameters of single tree. There are mainly two methods using small spot LiDAR data extracting forest LAD parameters, one method is based on gap probability theory, and the other is calculating LAD based on probability of the contaction between laser beam and canopy.

The first extraction method of LAD distribution is based on gap probability theory, which is defined as the unobstructed probability of vegetation when laser beams get through the canopy (Lovell, et al., 2003). The relationship between gap probability and LAD is shown as

$$P(\theta) = \exp\left\{-\frac{\mu h G(\theta)}{\cos(\theta)}\right\} \tag{2}$$

where $P(\theta)$ is the gap probability in direction of zenith angle, $\mu$ is leaf area density, $h$ is the height of whole canopy, and $G(\theta)$ is the average projected area in normal direction of observation a ngle, which related to leaf angle.

The second method is based on the contact probability b etween laser beam and canopy. Hosoi and Omasa (2006) presented a new method of Voxel-based Canopy Profiling (VCP). The function is as

$$\text{LAD}(h, \Delta H) = \frac{\cos\theta}{G(\theta)} \cdot \frac{1}{\Delta H}\sum_{k=m_h}^{m_{h+\Delta H}} \frac{n_I(k)}{n_I(k) + n_P(k)} \tag{3}$$

where $\theta$ is the apex angle of laser beam, $\Delta H$ is the thickness of horizontal layers, $n_I(k)$ and $n_p(k)$ is the number of the voxel values for 1 and 2 respectively, $n_I(k)/(n_I(k)+n_p(k))$ is the probability of laser contact canopy, and $\cos\theta(G(\theta))^{-1}$ is the c orrection factor for leaf angles and directions of laser beam.

Based on gap probability theory, Takeda changed radar laser emission angle, obtained gap probability at two viewing zenith directions, and used method of Norman-Campbell to obtain LAD optimum solutions of deciduous coniferous forest in Japan (Takeda, et al., 2008). The shadows among leaves influenced the size of canopy gap probability which leads to underestimation of parameters. The parameters fitting error is 1%—23%. Based on VCP method, Hosoi used ground based LiDAR data to extract canopy vertical LAD curve of Japanese camellia (Hosoi & Omasa, 2006) and beech (Hosoi & Omasa, 2007), and extracted wheat vertical LAD curve at different growth stages (Hosoi & Omasa, 2009). The extraction accuracies are 0.17, 0.21 and 0.45, respectively. The extraction precision was affected by leaf orientation, laser beam incident angle, and non-photosynthetic components (Omasa, et al., 2007). On the basis of VCP algorithm, Zande, et al. (2008) considered LiDAR observation angle and shadow effects from complex canopy structure, and established the virtual forest stands of three species including Fagus sylvatica, Platanus acerifolia, and Populus nigra based on stochastic L-system. Zande, et al. (2008) calculated the proportion of laser beam which pass through and intercepted by pixels in order to obtain LAD distributions of different vegetation types. The accuracy of the Zande's method is improved by 10%—20% than VCP algorithm.

Based on gap probability theory and contact frequency b etween laser beam and canopy theory, the method of using ground based small spot LiDAR data extracted forest LAD p arameter is simple and easier to implement. And the simulation results are consistent with reality. Therefore, these methods receive great attentions.

### 3.2 CHP extraction method from remote sensing

Full waveform LiDAR system records laser echo signals from top of canopy to ground. The echo waveform is closely r elated to vertical distribution of canopy. Full waveforms c ompletely record the reflection of surface vertical projection of canopy components (such as leaves, tree trunks, large branches and branchlets). Based on the "mid-section" echo signals, you can reconstruct the canopy vertical structures.

Based on MacArthur-Horn theory, you can reconstruct forest vertical structure profiles using full waveform digitizing LiDAR data. Lefsky and Cohen (1999a) had proposed an a mendment MacArthur-Horn method based on this theory. The new method assumes leaf distribution was horizontal and uniform, and ignores multiple scattering of internal vegetation. The first step is radar echo signals preprocessing. Data obtained form SLICER airborne laser radar system. According to background noises levels separated the ground and canopy echo s ignals. Then based on modified MacArthur-Horn equation, the cumulative vegetation coverage was converted into cumulative CHP curve. Finally, the cumulative CHP curve was normalized to canopy r elative CHP curve. This is the processes of airborne laser radar echo signals transformed into vegetation CHP curve. Kotchenova, et al. (2004) considering the scattering between c oniferous forest leaves and tree trunks, and eliminating the m ultiple scattering effects among tree trunks, he applied the i mproved the modified Lefsky's method to coniferous forest CHP extraction.

Based on modified MacArthur-Horn theory, Lefsky, et al. (1999a) using airborne LiDAR SLICER data extracted coniferous forest CHP curve in experimental zone of Cascade Mountains of Oregon Andrews and broad leaf forest CHP curve in eastern Maryland (Lefsky, et al., 1999b) and temperate deciduous mixed forest CHP curve (Harding, et al., 2001) at four growth stages. The error between simulation result and field measurement is 0.19—0.25. Results show that the canopy CHP curves extracted from full waveform digitizing LiDAR data are better reflect canopy vertical distributions. Kotchenova (2004) extracted black spruce coniferous forest CHP curve based on the modified method. The CHP distribution difference is increasing in space. The CHP extracted from Kotchenova's modified method is better reflecting vegetation differences in canopy vertical direction than Lefsky's method.

In summary, LiDAR technology is an effective means to e xtract forest vertical structural parameters. There is not having forest vertical structural products now. But some LiDAR data pre-processing and parameter extraction softwares can help non-professionals to process and apply LiDAR data, such as Tiffs software which can preprocess the LiDAR data, and generate DEM, DSM and CHM at the same time, and extract parameters like the single canopy shape, tree height and biomass (Chen, 2007), and IMH handling systems for airborne laser radar SLICER data which can process LiDAR signals convert into CHP curves (Lefsky, et al., 1999a). It can expand the appl-i cation fields of objects characteristic parameters extracting from LiDAR data.

## 4 BASED ON FIELD MEASUREMENTS VALIDATED THE ACCURACY OF FOREST VERTICAL PARAMETERS

Field measurement method is a direct way to obtain forest vertical structure parameters. The parameters that can be measured directly in field include tree height, breast diameter, LAI and LAD. The field measurements of forest tree height and breast diameter are relatively simple, which can obtain from d irectly measurement method. This paper does not introduce the direct measurements. The vegetation LAI or LAD acquired methods including field measurement method (direct and indirect measurement methods) and empirical relationships method based on field measurement parameters.

### 4.1 Field measurement method

According to different acquisition methods, the LAD field measurement is divided into direct and indirect measurement methods (Li & Wang, 1995). Direct measurement collected all leaves of each layer. The vegetation canopy is divided into several layers, then stratified cutting and collecting leaves along a given height from top to bottom, and measuring the leaves, stems and tassels of each layer. Based on direct measurements, Qin (1992) obtained the layered LAD measurements of winter wheat, soybeans, rice and other crops. Direct measurement method is suitable for lower crops, is not applicable for the relatively tall or non-destructive measurements vegetation, like forest or orchards.

Indirect measurements set up some instruments in vegetation layers at different heights, and measured the probability of vegetation components in contact with instruments or electromagnetic radiation intensity of different incident directions. Indirect measuring instruments mainly include LAI-2000, TRAC, HemiView canopy analysis system and so on. Based on canopy gap probability theory, Chen and Cihlar (1995) developed an instrument used to Trace Radiation and Architecture of Canopies (TRAC). The TRAC instrument was using canopy gap size distribution from field measurements to estimate trees clumping index, and indirectly measuring coniferous forest structures and LAI values (Chen & Cihlar, 1995). Indirect measurement results are usually used to validate the results from empirical relationships or remote sensing extractions.

### 4.2 Empirical function method

Empirical function method follows a certain assumptions, and creats linear or non-linear function relationships between filed measurements (such as tree height, LAI, height at the maximum LAD value and other parameters) and LAD parameters. Zhang, et al. (1999) made use of the $\beta$ function described LAD vertical distributions of coniferous forest canopy which presented a typically unimodal distribution. Ross (2000) using different parametric equations such as probability density functions of stem height, functions of stem height and stem leaf area, and v ertical distribution functions of stem leaf area, established the unary quadratic equations among different tree height $h$, LAI and LAD of willow coppice. The errors between simulation results and measurements are 10%—15%. Lalic and Mihailivic (2004) established an exponential relationship among LAD and tree height $h$, maximum leaf area density $L_m$ and its corresponding height $z_m$ parameters for pine, maple, silver birch and oak vegetation types. The root mean square error of LAD simulations is 0.16. The simulation results can factually describe the forest c anopy LAD variation with height.

Overall, the empirical relationship among tree height, LAI parameters and LAD is a practical method obtaining vegetation stratified parameters. The simulation results are agreed with reality. But the great limitation of empirical function method is regional discrepancy, and the empirical relationship is inconveniently extended to other regions. Therefore, the application of this method is subjected to certain restrictions.

## 5 VERTICAL STRUCTURE DISTRIBUTIONS OF TYPICAL VEGETATION TYPES

Currently, there are three methods obtain vegetation vertical structure parameters. The first method is empirical relationships between field measurements and vegetation vertical structure p arameters. The second method is extracting LAD from small spot LiDAR point cloud data based on gap probability or VCP theory. The third method is obtaining CHP parameters from full waveform digitization laser radar data based on MacArthur-Horn theory. But most of the extraction meathods aimed at single v egetation types, and the extraction vegetation types and ranges are limited. This paper summarizes the existing researches of f orest vertical structure parameters extraction. This paper collects three vegetation types vertical structural parameters containing eight species in totally, including winter wheat, soybeans and rice crops, fire and pine coniferous forest, camellia sasanqua, willow, maple, silver birch, oak and beech broadleaf forest. The following part will introduce the vertical structure distribution of some typical vegetation types.

### 5.1 Vertical structure distributions of the typical crop types

Qin measured LAD of winter wheat, soybeans, rice and other crops. The LAD distributions of three species crops are shown in Fig. 4. Qin had pointed out that exponential function can best describe the crop LAD curve variation with height (Qin, 1992; Xu, 2005).

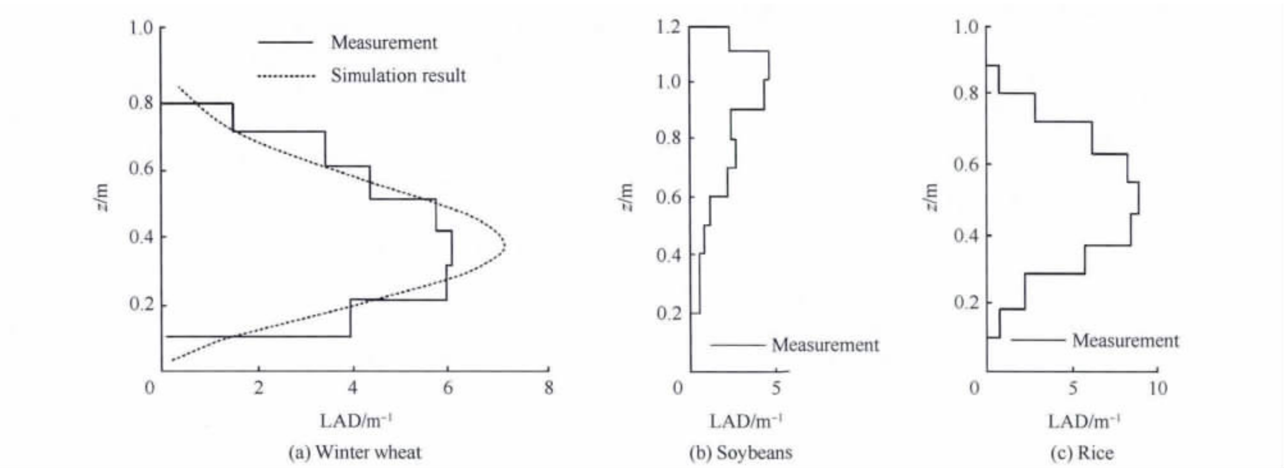


Fig. 4 The vertical distribution of leaf area density of typical crop types (Qin, 1992; Xu, 2005)

### 5.2 Vertical structure distributions of typical forest types

According to the discrepancy of vegetation types, forests i nclude broadleaf forest, coniferous forest and mixed forest. Due to the technology and methods extracted vegetation vertical structure parameters are limited, most of the existing research f ocused on single vegetation types. The following part will introduce vertical structural curves of several broadleaf and coni-f erous forests.

5.2.1 Coniferous forest

Vertical structures of coniferous forest are relatively simple; the canopy shapes of coniferous forest are pyramid and spheroidicity. Because coniferous forests grew in high elevations and cold regions, the lower vegetation growth is limited. The canopy vertical profile of coniferous forest can be described as a u nimodal distribution (Fig. 1(c)). The existing researches obtained vertical structural distributions of coniferous forest are agreed with the actual.

(1) Needle-leaf Area Density (NAD) of fir canopy is typi callyunimodaldistribution(Fig. 5(a)). NAD0, NAD1, NAD2and NAD represent current year, one year old, two years old, and total needle-leaf area density respectively. The results show that the largest NAD of fir appeared in upper part of canopy, and the smaller leaf age, the maximum NAD appeared at top of canopy (Zhang, et al., 1999).

(2) The exponential relationship between forest measurements parameters and LAD used to estimate LAD curve of pine (Fig. 5(b)). Simulation results (solid line) and observations (cross point) are in good agreement (Lalic & Mihailovic, 2004).

(3) Using ground-based radar data at August 26, 2003, based on gap probability theory Takeda, et al. (2008) extracted LAD curve of Japanese coniferous forests (Fig. 5(c)) (Takeda, e t al., 2008). Because the ground based LiDAR can measure the shrubs under coniferous forest canopy at the same time, LAD curve reached a second peak at 3 m height.

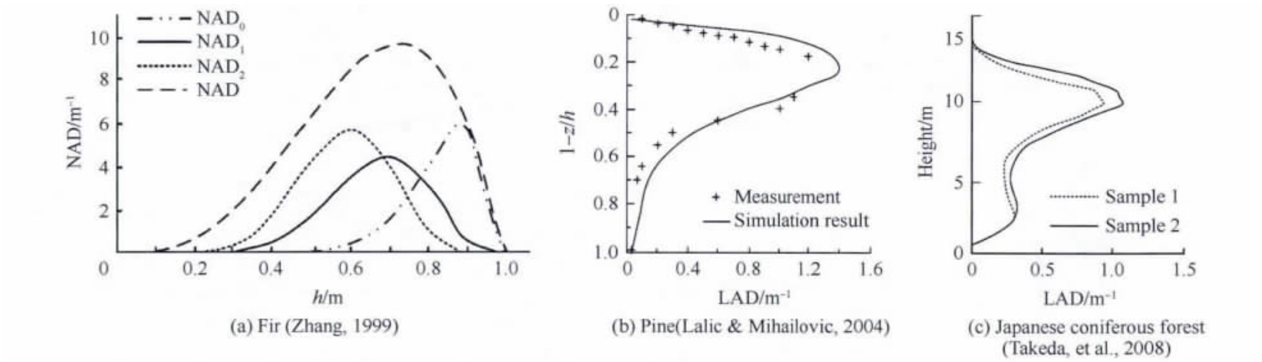


Fig. 5 The vertical distribution of leaf area density for several types of coniferous forest

5.2.2 Broadleaf forest

Compared with coniferous forest, the vertical structures of broadleaf forest is more complex. In fact, the vertical structure profiles of broadleaf forest can be described as a bimodal distribution. At first, the LAD reached peak at upper part of canopy, and then reached a second peak at the shrubs and grass growth region under canopy (Fig. 1(a)). However, due to the restrictions of measurement techniques and methods, the existing measurements obtained broadleaf structure parameters of single tree, and ignored the lower part vegetation growth. The next part will list several vertical distribution shapes of broadleaf canopy.

(1) Tree height of camellia sasanqua is about 2 m. Using ground based LiDAR data extract LAD distributions of camellia sasanqua based on VCP methods. The maximum LAD values appeared at the middle of canopy (Fig. 6(a)). The results are in accord with canopy shape of camellia sasanqua (Hosoi & Omasa 2006). Because small spot LiDAR point cloud data can recognize some vegetation detail informations, there are some discrete values at LAD curves.

(2) Vertical distributions of willow canopy simulated from unary quadratic equations among tree height $h$, LAI and LAD (Ross, et al., 2000). The shape of measurements curve and simulations curve is similar, and both of them presented the single peak distribution (Fig. 6(b)).

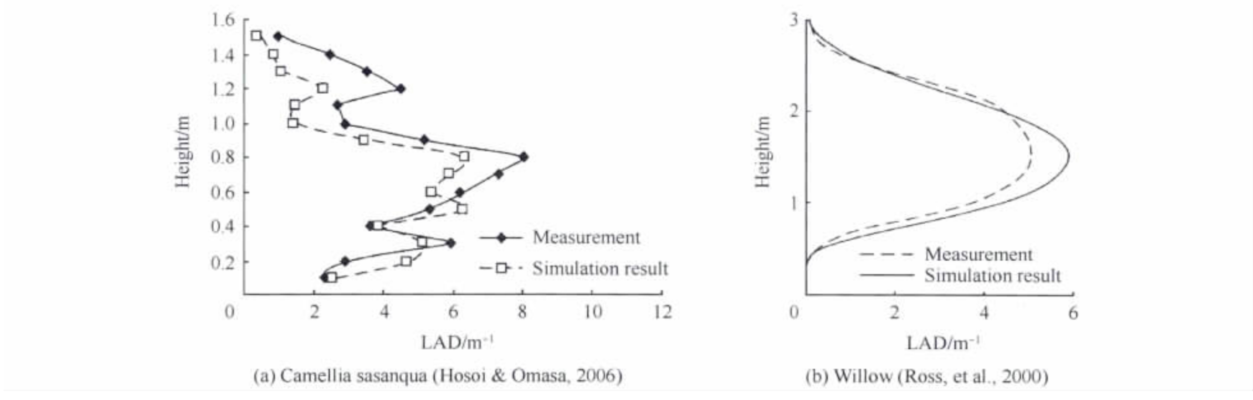


Fig. 6 The vertical distribution of leaf area density for lower types of broadleaf forest

(3) Based on exponential relationship between forest measurement parameters and LAD to simulate LAD curves of maple, silver birch and oak varies with heights (Fig. 7(a), F ig. 7(b), Fig. 7(c)) (Lalic & Mihailovic, 2004). Did not

consider the impacts of lower shrubs and grasses, the trends of canopy simulation values (solid line) was similar with observations (cross point), both were followed a unimodal distribution. For beech tree, making use of ground based LiDAR data based on VCP method to extract LAD curve (Fig. 7(d)) (Hosoi & Omasa, 2007). The results show that shape of canopy was f ollowed unimodal distribution and LAD reached maximum at middle to upper part.

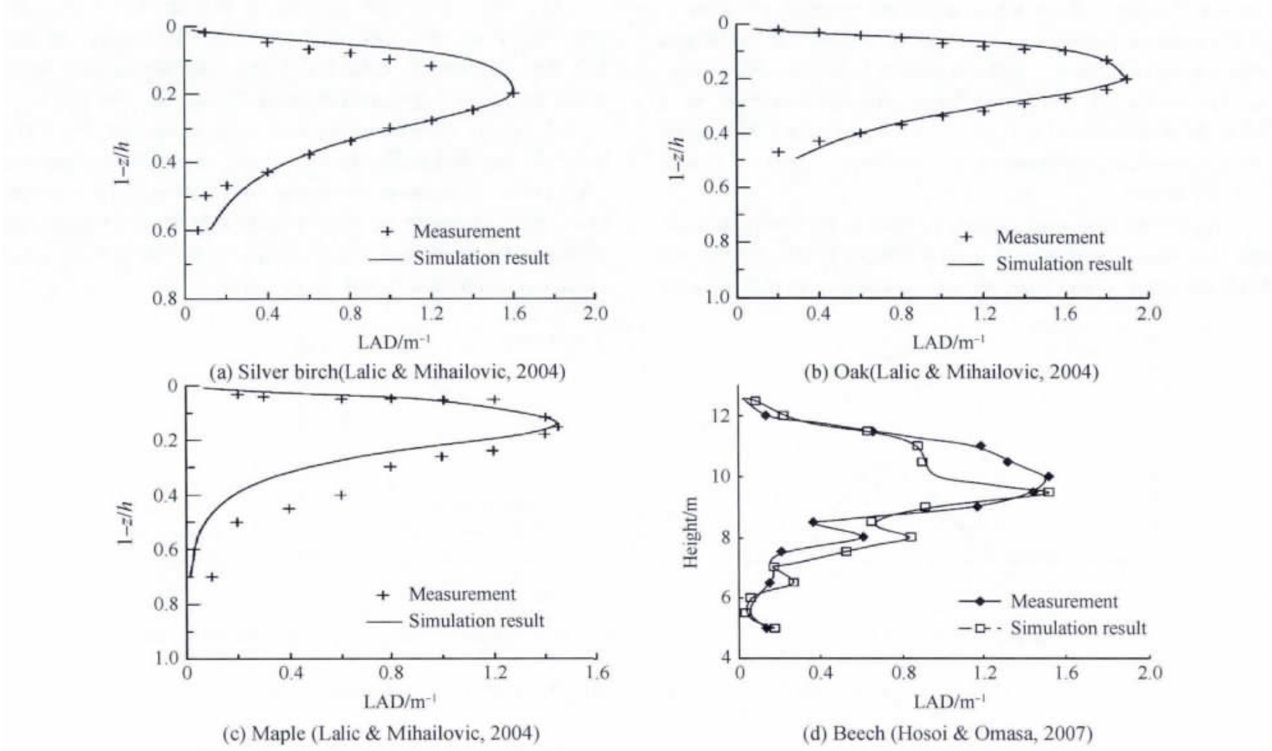


Fig. 7 The vertical distribution of leaf area density for several types of broadleaf forest

## 6 PROSPECT AND DISCUSSION

At present, many researchers carry out numerous studies on forest monitoring at domestic and abroad. It is feasible to extract forest LAD and CHP based on microwave remote sensing and active laser radar technology. But there are still some problems when extracting forest vertical structural parameters from remote sensing:

(1) Forest vertical structure parameters are extracted at small regions and single vegetation type. Forest structure parameters extracted from remote sensing include field measurement and ground based LiDAR observation, and airborne InSAR or LiDAR observations at small region. Field measurement and ground based LiDAR observation usually obtained LAD or CHP parameters of single vegetation type (Ross, et al., 2000; Hosoi & Omasa, 2006, 2007). However, the airborne LiDAR can get c anopy height profile at small region (Lefsky & Harding, 1999a, 1999b), the range of vegetation LAD and CHP extracted is limited, and the required manpower and material costs are higher c orrespondingly.

(2) Lack corresponding products of forest vertical structure parameters. Researches of forest vertical structure parameters e xtracted from remote sensing technology is in the exploratory stage, and each research faces many problems. Therefore, there is not providing corresponding products of forest vertical structure parameters. The active LiDAR technology is considered as an e ffective means to extract forest vertical structural parameters. There are some pre-processing and parameter extraction software for LiDAR data, such as Tiffs and IMH processing system for SLICER data. These softwares help others to extract forest vertical structure parameters from LiDAR data.

Extraction researches of forest vertical structural parameters still need further studies at data source and extracted algorithm in the future:

(1) The researches of forest vertical structure extracted from spaceborne data are relatively fewer. There is a spaceborne GLAS system which is applied in forest resource survey, ice sheet topography measurement, clouds and atmospheric properties monitoring, and tree height and crown monitoring. With the development of spaceborne LiDAR sensor technology and researches, it needs to carry out the extraction of forest vertical structure parameters based on spaceborne LiDAR system. It will expand the extraction ranges of forest vertical structure p arameters in spatial.

(2) The forest vertical structure not only affects the growth and distribution of upper and lower plants, but also affects electromagnetic radiation transmission within forest. Therefore, it needs to understand the forest internal structure and mechanism of electromagnetic radiation transmission, and carry out some r esearches about the quantitatively description and variation m onitoring of forest vertical structure parameters, and couple v ariety of remote sensing technologies to extract forest vertical structural parameters.

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# 森林垂直结构参数遥感反演综述

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摘 要: 随着遥感技术的发展，林业遥感从早期森林分类制图的定性研究，逐步发展到森林整体特性的遥感定量反演研究。目前利用遥感反演的森林叶面积指数、生物量、叶绿素浓度、碳储量等参数以描述森林生化理化特征、水平结构特征为主，而描述森林垂直结构的参数较少。本文针对不同高度处森林的叶面积密度和冠层垂直高度廓线参数，综述了遥感获取森林垂直结构参数的方法以及典型地表类型的垂直结构参数曲线，并总结了森林垂直结构参数提取方法中存在的问题，探讨未来研究方向。

关键词: 森林垂直结构，叶面积密度，冠层高度廓线，InSAR，激光雷达

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## 1 引 言

森林是陆地上面积最大、分布最广、组成结构最复杂、物质资源最丰富的生态系统，也是自然界功能最完善的资源库、生物基因库，及水、碳、养分及能源储存调节库，对改善生态环境、维护生态平衡具有不可替代的作用(庞勇 等，2005)。

森林遥感一直是遥感应用研究的一个重要方向。20 世纪 70 年代初航空遥感数据最早用于林业森林制图，到 70 年代中后期高分辨率航天遥感的发展促进了林业资源分类识别与监测研究(李芝喜，1990)。随着遥感技术的发展，利用多光谱、高光谱、雷达与激光雷达数据等遥感数据对森林类型和结构特征开展了广泛的监测与评估研究。目前，主要使用光学遥感、微波遥感以及主动激光雷达技术监测森林生长状态(庞勇 等，2005)。遥感可获取的参数包括森林的叶面积指数 LAI (Leaf Area Index)、生物量、林冠生化组分浓度(如叶绿素、氮和水分含量、碳储量等)、树高、树冠形状、森林类型、郁闭度及森林健康状况因子等，这些参数侧重描述森林生化理化特征和水平结构特征。

基于遥感手段提取的森林生化物理参数主要针对植被在地面水平分布状态和格局而言，针对植被垂直异质性反演的研究较少。植被内部复杂的垂直结构是造成遥感提取森林参数误差的主要因素，因此不少学者展开森林垂直结构参数提取研究。森林垂直结构体现了森林在垂直方向上的层次性，即构成群落的植物个体在垂直空间上的配置方式(郑景明 等，2008)。森林群落的垂直成层性是植被对阳光、养料和水分等自然选择的结果，直接影响树木生长和植物群落的演替过程(韩玉萍 等，1999)。因此森林垂直结构对提高森林生物量、叶面积指数估测精度和开展森林演替、碳循环、初级生产力研究具有重要意义(De Wasseige 和 Defourny，2002)。目前森林垂直结构参数遥感提取已成为林学、生态环境学和遥感科学研究的热点(何祺胜 等，2009; 谭炳香 等，2008)。

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## 2 森林垂直结构分布特征及遥感参数表达

### 2.1 森林垂直结构特征描述

森林是以树木和其他木本植物为主的生物群落,与生物圈及其他水、陆生态系统之间不断地进行着物质与能量交换。在植被群落中,由于各个植被种群分别占据了不同的空间,从而使群落形成了一定的空间结构。这种空间结构又可分为垂直结构和水平结构(孙鸿烈,2000)。水平结构是指植物群落在地面上的分布状态和格局,例如荒漠中规则分布的灌木、林中簇生分布的灌丛等;而垂直结构主要是指群落在空间上的垂直分层现象。

森林垂直结构描述了森林植物地上同化器官(枝、叶)在空中的排列成层现象,它与光的利用有关。林冠层吸收了大部分光辐射,光照强度受树干枝叶的拦截而逐渐减弱,因此森林自上而下分别形成乔木树冠层、下木层、灌木层、草本植物层和苔藓等草被层(陈阅增,1999)(如图1(a)所示)。上层乔木层是森林中最主要的层次,它能够充分利用阳光;而穿过乔木层的光有时仅占到达树冠全光照的十分之一,因而乔木树冠下错落分布着能够有效利用弱光的灌木层和草本植物层;草本层以下还有更耐荫的苔藓和地衣等地被植物层(朱正威 等,2004)。

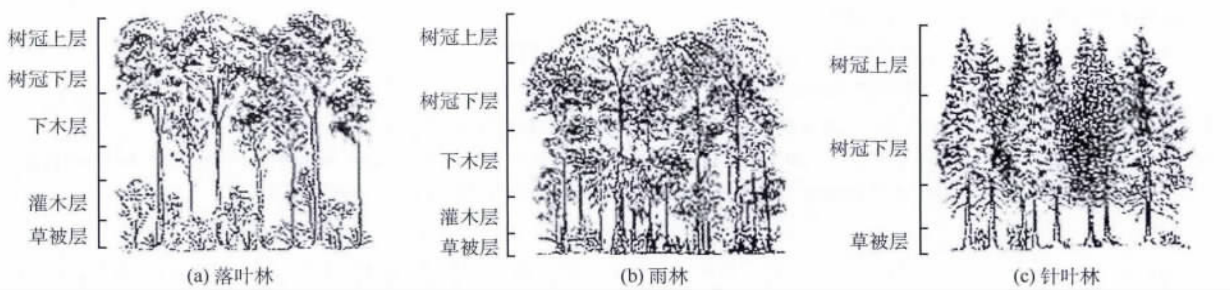



图1 典型森林类型垂直分层结构图(陈阅增,1999)

森林群落的垂直结构是林内植物适应不同生态梯度的结果,它显著提高了植物利用环境资源的能力,不同森林类型具有不同的垂直结构,水热条件越优越,群落垂直结构越复杂,则内部相互作用机理也越复杂,例如热带雨林的垂直结构比阔叶林和针叶林要复杂多(图1(b)(c))。

### 2.2 森林垂直结构参数

林业上描述森林结构的参数包含树高、胸高断面积、林分郁闭度、林分密度、蓄积量和生物量等(赵峰 等,2008),这些参数宏观地描述了森林空间分布格局及其生产力。而利用遥感提取森林参数的研究与林业研究侧重点有所不同,遥感提取的森林结构参数包括森林生物物理参数(如提取树高和单木树冠轮廓、识别森林类型、估算LAI和生物量、估测郁闭度和林分密度等)、森林生物化学参数(如叶绿素含量、碳储量等)及森林健康状况因子等(刘清旺 等,2009;谭炳香 等,2008;徐天蜀,2008;杨曦光 等,2010;杨永恬 等,2010;赵峰 等,2008),这些参数侧重反映森林的内部属性和结构特征。

在上述描述森林结构的参数中,能够体现森林垂直分层状况的参数较少,而本文重点关注描述森林垂直结构特征的参数。在林业上,树高不仅是划分不同林层的依据,也是描述森林垂直结构的参数之一,但树高提供树木高度数值,并不能体现树木在垂直方向上的生长状态。因此,在遥感中,采用表述不同高度处叶面积分布情况的LAD曲线,和冠层在垂向上叶片空间分布的CHP参数来描述森林在垂直方向上的生长状况。

#### 2.2.1 叶面积指数

LAI为无量纲参数,是描述植被冠层结构基本的参量之一,最早定义为单位地表面积上参与光合作用的单面叶子总面积(Watson,1947)。这个定义适用于正反叶片叶面积相等的阔叶树木,对于弯曲或褶皱的非平整叶片、针叶树的圆柱形或半圆柱形叶片而言,该定义存在很大局限。

1981年Ross进行野外LAI测量时通过勾画叶子轮廓测量叶面积,因此测量非平展叶片或针叶叶片时,将叶片的投影面积作为LAI值(Ross,1981;Chen和Black,1992)。此后,不少学者将LAI定义为单位地表面积上叶片的投影面积(Bolstad和Gower，1990；Smith，1991），该定义存在一个关键问题是如何选择投影角度。

目前使用最广泛的是 Chen 和 Black（1991）对 LAI 的定义，即 LAI 为单位地面面积上总叶面积的一半（Chen 等，1991）。但在研究非平展叶片如针叶时该定义不再适用，因此 Chen 和 Black（1992）基于叶片截留光的概念提出适合针叶林或非平展叶片的 LAI 定义，将 LAI 定义为单位地表面积上叶片总拦截面积的一半，该定义不仅体现了叶片拦截辐射通量的物理意义，同时也具有一定的生物学含义。

### 2.2.2 叶面积密度

LAI 用于描述连续植被冠层的总叶面积，但不能体现冠层内叶面积随高度的分布状况。因此需要引入一个表征植被垂直方向上不同分层内叶面积差异的参数，即 LAD。LAD 定义为冠层高度 $z$ 处，单位体积内参与光合作用的叶子单面面积总和（Myneni 等，1989；Weiss 等，2004）。层内植被越茂盛该层 LAD 值越大（图 2）。冠层高度 $h$ 内所有层 LAD 之和即为冠层 LAI 值，LAD 和 LAI 的关系可以表示为：

$$\mathrm{LAI} = \int_0^h \mathrm{LAD}(z')\,\mathrm{d}z' \qquad (1)$$

LAD 描述叶面积分布随高度 $z$ 变化，它随不同树种、不同生长阶段及环境干扰等因素变化，而且是生态过程模型的重要输入参数。

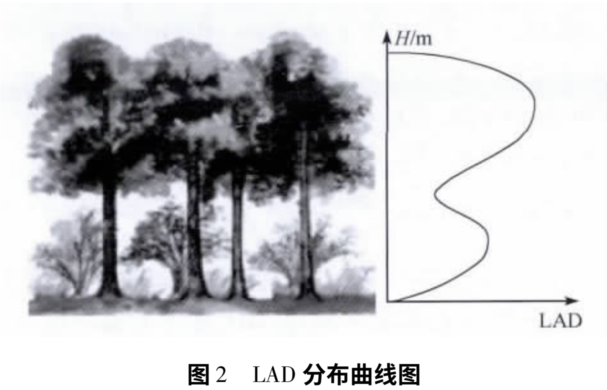



图 2　LAD 分布曲线图

### 2.2.3 冠层高度廓线

冠层高度廓线 CHP（Canopy Height Profile）表示冠层内所有组分的表面积（包括叶片和木质部分）随高度变化的函数；树叶高度廓线 FHP（Foliage Height Profile）表示从地表到冠层范围内，植被所有叶子表面面积随高度分布的函数（Lefsky 等，1999a）。这两个参数都描述各植被层叶子生长密度随高度变化情况，只是描述的植被组分有所区别。

CHP 是在 LiDAR 探测技术应用于森林垂直结构监测的背景下提出的。由于大光斑 LiDAR 能够完整记录激光脉冲初次和末次返程信号之间的振幅变化，所记录的波形与树冠垂直结构密切相关（Harding 等，2001），植被分布密集处 LiDAR 回波强度大（图 3），根据这些雷达回波可以重建林分冠层的垂直结构。目前利用全波形大光斑 LiDAR 提取森林结构参数时主要将回波信号转换成描述植被垂直结构的 CHP 曲线。

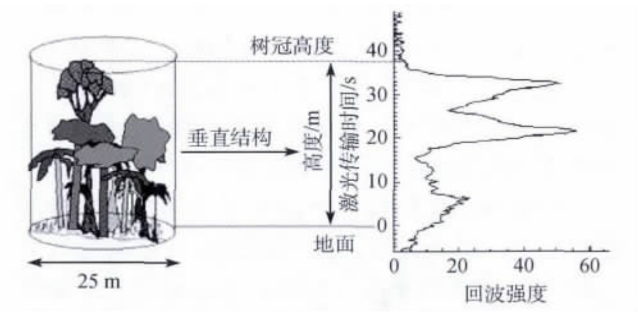



图 3　大光斑 LiDAR 森林回波波形示意图
（Drake 等，2002）

## 3　遥感提取森林垂直结构参数方法

在森林遥感监测中，用来描述森林垂直结构特征的参数主要包括 LAD 和 CHP。下面对这两个参数遥感反演研究现状进行综述。

### 3.1 LAD 遥感提取方法

遥感提取 LAD 特征参数的模型反演方法是指基于植被反射和散射电磁辐射信号与植被结构参数之间的统计或物理模型，利用遥感获取的电磁波信号反演植被结构参数。在森林冠层中，树叶、树枝和树干等都可以视作散射体，这些散射体的反射或散射作用是产生雷达回波的主要部分，其散射密度大小取决于植被散射体的方向，比如树枝和树干的垂直方向组分。

微波遥感中，雷达极化与干涉方式对植被不同组分的响应存在差异，能够得到不同的雷达回波信号。利用微波数据反演植被结构参数时，以雷达方程为基础，建立雷达相关系数与植被结构参数之间的统计或物理模型，代入回波信号反演植被结构参数。目前已开展基于极化与干涉雷达回波信号估测松树或者北方森林群落的 LAD 分布的研究（Treuhaft 等，1999，2000，2006，2009）。

激光雷达技术通过主动获取目标3维坐标信息估测森林参数,小光斑激光雷达点云数据记录脉冲信号与植被组分的接触概率,基于间隙率或叶片拦截率理论,建立激光雷达回波信号与LAD之间的统计模型,成功用于地基小光斑LiDAR点云数据提取单株植被或单一类型树种的LAD曲线。

### 3.1.1 微波获取方法

在微波遥感中,极化雷达对植被分布和取向比较敏感,而干涉雷达(InSAR)对植被空间分布敏感(Treuhaft和Cloude, 1998)。因此,利用多基线多频率干涉仪的振幅和相位信息(Treuhaft等, 2000)或单一基线极化干涉雷达多个高度数据(Treuhaft等, 1999)可以估测森林结构参数和消光特性,这说明基于微波数据提取森林结构参数具有可行性。

利用InSAR数据反演植被垂直结构的关键问题即是建立相干方程系数与植被垂直结构参数之间的关系,首先将相干方程表达为植被体和地表组分的定量关系式,再根据雷达极化干涉回波信号求解出植被结构参数(Treuhaft和Cloude, 1998)。Treuhaft等人(2006)利用C波段InSAR数据基于物理模型,通过求取6个不同基线的相位和相关系数、消光系数和相对密度之间的最小二乘解,反演植被相对密度廓线,模拟结果与实际情况拟合较好。陈曦等人(2009)利用双基线极化干涉数据基于局部极化干涉相干优化算法提取植被垂直结构剖面,其拟合结果与仿真建模模拟结果误差小于0.6。

另外,多基线极化InSAR技术能够有效识别植被覆盖,可用于估算植被参数或探测森林垂直剖面特征等(庞蕾 等, 2010)。Treuhaft和Chapman(2009)假定相对LAD服从高斯分布并修订InSAR相干方程表达式,利用多基线机载AirSAR C波段数据直接求取热带雨林地区植被LAD分布,模拟结果精度为17%—19%。模拟精度受雷达干涉信号的相关系数定标差异与相函数误差影响。

微波遥感数据能够获取植被垂直尺度信息,但单一传感器获取的森林垂直结构信息能力有限,借助高光谱数据对植被光学特征的敏感响应,展开多个传感器联合反演LAD的研究。Treuhaft等人(2002)首次尝试利用Radar和高光谱数据联合反演LAD,假设相对密度函数仅受Radar数据影响、LAI只受高光谱数据影响,利用雷达相关方程与相对密度函数之间的关系求解植被LAD和LAI值,其中LAD模拟值与实测值误差为1%—2%,但该方法存在一个主要问题即联合反演的假设条件缺乏考虑其他参数对Radar和高光谱数据的依赖,这种方法仍处于研究阶段并未推广应用。

由于干涉雷达方程表达式比较复杂,在求解过程中需要设置较多辅助参数、及边界条件,一定程度上影响了LAD提取精度。因此利用微波数据提取LAD的方法并未得到广泛应用。

### 3.1.2 LiDAR估测方法

鉴于LiDAR对森林具有很强的穿透能力,在森林参数获取方面具有显著优势,因此广泛应用于林业参数的定量遥感估算。小光斑LiDAR光斑尺度比较小,单木范围内就能获取较多的点云数据,可以进行单木的参数测量。利用小光斑LiDAR提取森林LAD参数主要有两种方法,一种方法基于间隙率理论,另一种方法通过计算激光光束与冠层的接触频率估算LAD值。

第1种方法基于间隙率理论提取LAD分布。间隙率定义为激光光束穿过植被冠层时未被植被体拦截的概率(Lovell等, 2003),间隙率与LAD存在如下关系:

$$P(\theta) = \exp\left\{-\frac{\mu h G(\theta)}{\cos(\theta)}\right\} \tag{2}$$

式中,$P(\theta)$表示天顶角方向的间隙率;$\mu$为叶面积密度即LAD;$h$为整体冠层高度;$G(\theta)$为观测角法线方向的平均投影面积,与叶倾角有关。

第2种方法基于激光光束与冠层的接触频率这一思想。以该思想为基础Hosoi和Omasa(2006)提出基于体元素的冠层分析VCP(Voxel-based Canopy Profiling)方法,通过计算激光接触每层冠层叶片的概率求得LAD值,公式如下:

$$\mathrm{LAD}(h,\Delta H) = \frac{\cos\theta}{G(\theta)} \cdot \frac{1}{\Delta H}\sum_{k=m_k}^{m_{h+\Delta H}} \frac{n_I(k)}{n_I(k) + n_P(k)} \tag{3}$$

式中,$\theta$为激光光束天顶角;$\Delta H$为水平层厚度;$n_I(k)$和$n_P(k)$分别表示体像元的数值为1或2的个数,则$n_I(k)/(n_I(k)+n_P(k))$用于表示激光接触冠层的频率;$\cos\theta(G(\theta))^{-1}$为叶倾角和激光光束方向的校正因子。

基于间隙率理论,Takeda等人(2008)通过改变地基雷达激光发射角度,获取两个观测天顶角方向上的间隙率,并用Norman Campbell方法得到日本落叶针叶林LAD的最优化解。由于树叶之间存在遮挡影响冠层间隙率大小,造成模拟低估现象,参数拟

合误差为 1%—23%。基于 VCP 方法,Hosoi 等人利用地基 LiDAR 数据先后提取了日本山茶树(Hosoi 和 Omasa,2006)和榉树(Hosoi 和 Omasa,2007)树冠垂直 LAD 曲线、以及小麦不同生长阶段垂直 LAD 曲线(Hosoi 和 Omasa,2009),提取精度分别为 0.17、0.21 和 0.45。利用 VCP 方法提取的植被 LAD 曲线与实测值接近,提取精度受到叶片叶倾角取向、激光光束入射角度以及非光合作用组分等因素影响(Omasa 等,2007)。Van der Zande 等人(2008)在 VCP 算法基础上考虑激光雷达观测角度或复杂冠层结构遮挡产生的阴影作用,利用随机 L 系统建立欧洲山毛榉、法国梧桐和欧洲黑杨 3 个树种的真实场景,通过模拟地基 LiDAR 激光光束穿过像素体或被像素体拦截的比例,求取各植被类型 LAD 分布曲线。考虑阴影影响的方法比 VCP 算法精度提高了 10%—20%。

基于间隙率和激光光束与冠层接触频率的理论方法,利用地基小光斑 LiDAR 提取森林 LAD 参数,其模型简单、易于实现,且模拟结果符合实际,因此受到学者的广泛关注。

### 3.2 CHP 遥感提取方法

全波形激光雷达系统数字化记录了冠层顶到地面间的激光回波信号,其中回波波形与冠层垂直分布密切相关。全波形完整地记录了冠层组分(如叶、树干、大枝和小枝)表面垂直投影的反射,根据这些“中间截面”的回波可以部分重建林分冠层的垂直结构。

利用全波形数字化激光雷达数据重构森林垂直结构廓线主要基于 MarArthur-Horn 理论,Lefsky 等人(1999a)在该理论基础上提出修正的 MarArthur-Horn 方法,新方法假设叶片水平均一分布、并忽略植被内部多次散射的影响,首先对机载激光雷达 SLICER 回波信号进行预处理,识别原始信号的背景噪音,根据背景噪音程度分离地面与冠层的回波信号,得到消除了背景噪音的回波信号;然后利用 MarArthur-Horn 方程将累积植被覆盖度转化成累积 CHP 曲线;最后将累积 CHP 曲线进行归一化,得到冠层相对 CHP 曲线,实现了从机载激光雷达回波信号转化为植被 CHP 曲线的过程。随后 Kotchenova 等人(2004)在修正的 MarArthur-Horn 方法上进行改进,考虑针叶林叶片和树干之间的散射作用、并消除树干之间的多次散射影响,得到适用于针叶林树木的 CHP 提取方法。

基于修正的 MarArthur-Horn 理论,已有学者利用机载激光雷达 SLICER 数据,分别提取了俄勒冈州喀斯喀特山脉安德鲁斯实验区的针叶林(Lefsky 等,1999a)、马里兰东部的阔叶林(Lefsky 等,1999b)以及温带落叶混交林(Harding 等,2001)4 个生长阶段的 CHP 曲线,与地面测量数据对比误差在 0.19—0.25,结果表明利用全波形数字化激光雷达数据提取的冠层 CHP 曲线能够较好地反映冠层叶片垂直分布情况。Kotchenova 等人(2004)改进方法提取的黑云杉针叶林 CHP 曲线空间分布差异增大,比 Lefsky 方法得到的 CHP 曲线更好地反映植被在冠层垂直方向上的差异。

由此可以看出,LiDAR 技术是目前提取森林垂直结构参数的有效手段。虽然没有具体的产品,但已有一些 LiDAR 数据预处理与参数提取软件,如 Tiffs 软件能够实现激光雷达数据预处理,同时生成 DEM、DSM、CHM,并提取单株树冠、树高、生物量等参数(Chen,2007),另外 IMH 处理系统针对机载激光雷达 SLICER 数据实现从 LiDAR 信号转换为 CHP 曲线过程(Lefsky 等,1999a)。这些可视化软件能够帮助非专业人员处理和使用 LiDAR 数据,拓宽了 LiDAR 数据提取地物特征参数的应用领域。

## 4 基于地面测量数据验证森林垂直结构提取精度

野外测量方法是获取森林垂直结构参数最直接的途径。在野外能够直接测量的参数包括树高、胸径、树木 LAI 和 LAD。森林树高和胸径测量相对简单,采用直接测量方法即可获取,此处不做扩展描述;获取植被 LAI 或 LAD 方法包括野外测量法(直接测量和间接测量方法)和基于地面测量数据的经验关系方法。

### 4.1 野外测量法

按照获取方式不同,野外测量 LAD 方法分为直接测量和间接测量两种方法(李小文和王锦地,1995)。直接测量采用分层收集方式,需要将植被分成若干层,从上到下沿给定高度分层剪下并收集起来,并对每一层的叶、茎、穗等进行分别测量。覃文汉等人(1992)对农作物进行了直接测量,得到冬小麦、大豆、水稻等农作物的分层 LAD 测量结果。这种直接测量方法适用于低矮作物,对于相对高大

或不宜作破坏性测量的森林、果园等,该方法不适用。

间接测量法是将测量仪器安置在不同高度植被层中,测量植被组分与仪器接触比例或不同方向入射的电磁辐射强度,从而推算出 LAI 或者 LAD。间接测量仪器主要包括 LAI-2000、TRAC、HemiView 冠层分析系统等,其中陈镜明等人研制的 TRAC 冠层结构辐射跟踪仪基于冠层间隙率模型,利用实测获取的冠层间隙尺寸分布,推算叶片聚集指数(Clumping Index),实现间接测量针叶林的结构和 LAI (Chen 和 Cihlar,1995)。间接测量结果通常用于经验关系或遥感提取结果的验证。

### 4.2 经验函数法

经验函数方法通过限定某些假设条件,建立地面实测数据(如树高、LAI、LAD 最大值对应的高度等参数)与 LAD 参数之间的线性或非线性函数关系。张小全等人(1999)利用 $\beta$ 函数描述针叶树冠 LAD 垂直分布情况,针叶树冠垂直分布呈现典型的单峰分布。Ross 等人(2000)采用不同的参数化方程如茎高的概率密度函数、茎高与茎叶面积函数、茎叶面垂直分布形状函数,建立柳树矮林不同树高 $h$ 与 LAI、LAD 之间的一元二次关系式,模拟值与实测数据存在 10%—15% 的误差。Lalic 和 Mihailivic (2004)针对松树、枫树、白桦树和橡树植被类型,建立树高 $h$、叶面积密度最大值 $L_m$ 及其相应高度 $z_m$ 3 个参数与 LAD 之间的指数关系式,LAD 模拟值均方根误差为 0.16,模拟结果能够较真实地描述森林冠层内 LAD 随高度的变化。

总体来说,建立实测树高、LAI 等参数与 LAD 经验函数关系是切实可行的获取植被分层结构参数的方法,从参数拟合精度来看模拟结果符合实际。但经验关系法应用的最大局限在于方法存在区域性差异,不便扩展到其他区域,因此经验方法应用受到一定限制。

## 5 典型植被类型的垂直结构分布

目前获取植被垂直结构参数的方法包括:建立野外测量参数与植被垂直结构参数的经验关系式;或采用小光斑 LiDAR 点云数据基于间隙率或 VCP 方法提取 LAD;或利用全波形数字化激光雷达数据基于 MarArthur-Horn 理论提取 CHP 参数。但上述植被垂直结构参数提取研究大都针对单一植被类型,并且提取的类型有限、提取范围也比较小。本文总结了目前已有的森林垂直结构参数提取研究,总共获取冬小麦、大豆和水稻 3 种农作物及杉木、松树等针叶林,山茶树、柳树、枫树、白桦树、橡树和榉树等阔叶林,共 3 种植被类型涵盖 8 个树种类型的垂直结构参数。下面介绍几种典型植被类型的垂直结构分布曲线。

### 5.1 典型农作物类型垂直结构分布

覃文汉等人分层测量了冬小麦、大豆、水稻等农作物 LAD,得到 3 种农作物类型的 LAD 随高度变化曲线(图 4),并指出农作物 LAD 随高度变化曲线与指数函数关系式拟合效果最好(覃文汉,1992;徐希孺,2005)。

### 5.2 典型森林类型垂直结构分布

按照植被类型划分,森林主要包括阔叶林、针叶林和混交林。由于获取植被垂直结构参数技术和方法有限,已有的研究仅限于单一森林类型,因此下面分别介绍几种具体阔叶林和针叶林树种的垂直结构曲线。

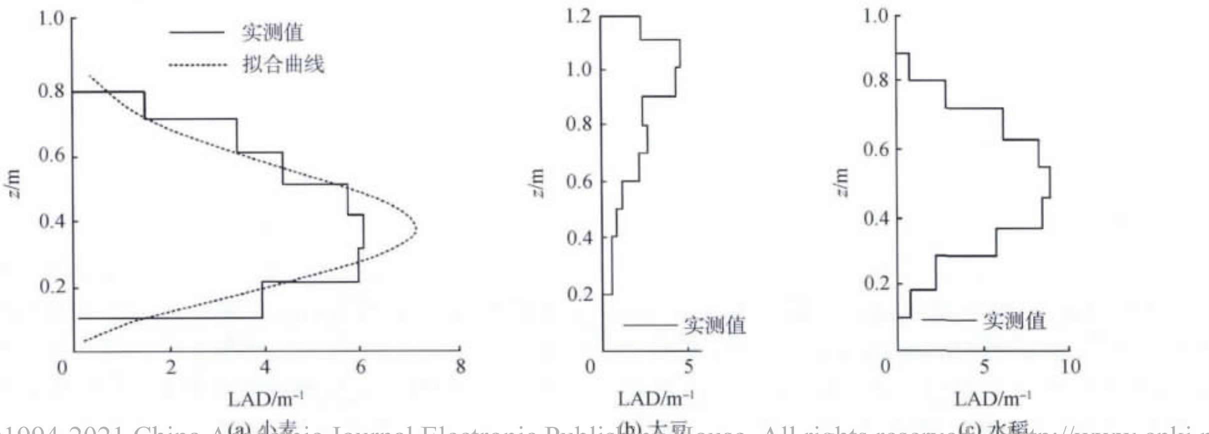





图 4 典型农作物叶面积密度垂直分布图(覃文汉,1992;徐希孺,2005)

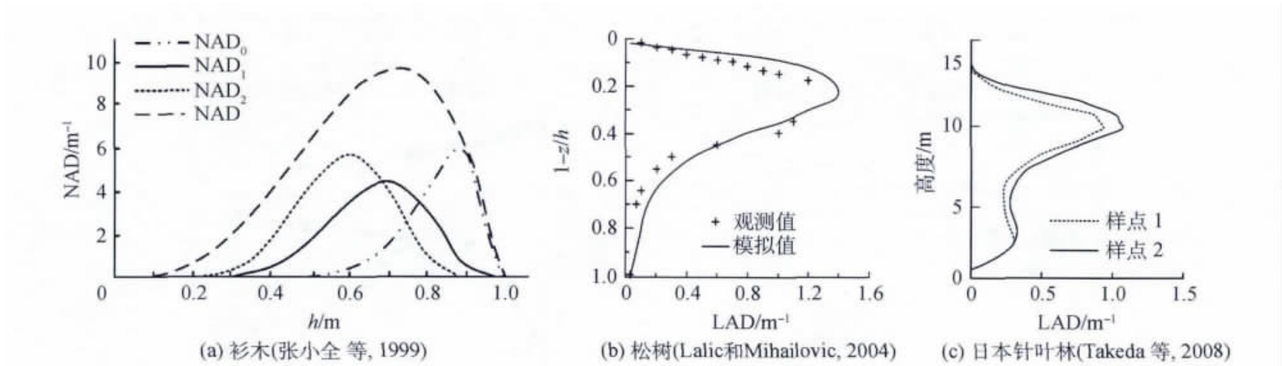
#### 5.2.1 针叶林类型

针叶林垂直结构比较简单,其树冠形态多为塔形、椭球形等,由于针叶林生长在海拔较高的寒冷地区,下层植被生长受到限制,因此树冠垂直廓线主要呈现单峰分布(图 1(c))。已有研究获取的针叶林垂直结构分布比较符合实际规律。

(1) 杉木树冠针叶面积密度 NAD(Needle-leaf Area Density) 曲线为典型单峰分布(图 5(a)),其中 NAD0、NAD1、NAD2 和 NAD 分别表示当年、1 a、2 a树龄及总的针叶树冠叶面积密度,结果表明杉木最大 NAD 出现在树冠中上部,叶龄越小 NAD 最大值越趋向于树冠顶部(张小全 等,1999)。

(2) 松树类型 LAD 曲线通过建立森林实测参数与 LAD 之间的指数关系式得到(图 5(b)),其模拟值(实线)与观测值(十字点)吻合较好(Lalic 和 Mihailovic,2004)。

(3) 日本针叶林 LAD 曲线利用 2003 年 8 月 26 日地基雷达数据基于间隙率理论提取得到(图 5(c))(Takeda 等,2008)。由于地基雷达同时测量了针叶林下层生长的灌木,因此在 3 m 高度处出现 LAD 曲线的次峰值。



(a) 杉木(张小全 等, 1999) (b) 松树(Lalic和Mihailovic, 2004) (c) 日本针叶林(Takeda 等, 2008)

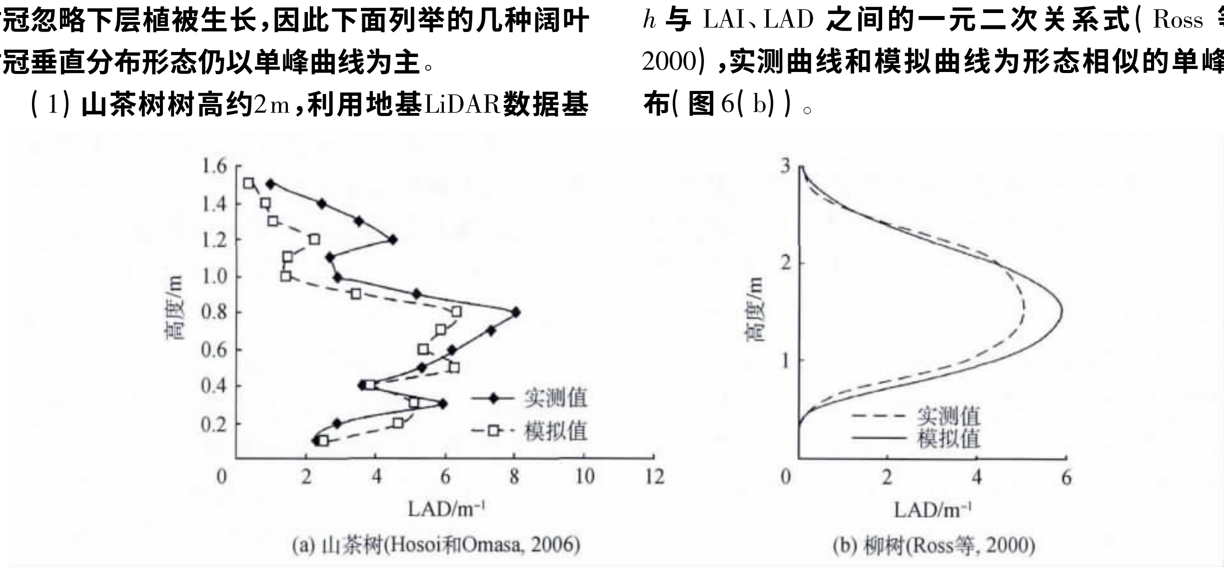
图 5 几种针叶林类型叶面积密度垂直分布图

#### 5.2.2 阔叶林类型

与针叶林相比,阔叶林垂直结构比较复杂。在实际中阔叶林垂直结构廓线可以描述为双峰分布,首先在冠层中上部达到峰值,然后在底部灌丛和草被茂盛区达到次峰值(图 1(a))。但是由于测量技术和方法有限,已有的测量数据仍是针对单棵阔叶树冠忽略下层植被生长,因此下面列举的几种阔叶树冠垂直分布形态仍以单峰曲线为主。

(1) 山茶树树高约2 m,利用地基LiDAR数据基于 VCP 方法提取的山茶树 LAD 曲线在中部达到最大值(图 6(a)),比较符合山茶树树冠形态(Hosoi 和 Omasa,2006)。由于小光斑雷达点云数据获取部分植被细节信息,因此得到的 LAD 曲线存在不连续值。

(2) 柳树矮林树冠垂直分布曲线采用不同树高 $h$ 与 LAI、LAD 之间的一元二次关系式(Ross 等,2000),实测曲线和模拟曲线为形态相似的单峰分布(图 6(b))。



(a) 山茶树(Hosoi和Omasa, 2006) (b) 柳树(Ross等, 2000)

图 6 低矮阔叶林类型叶面积密度分布

(3)枫树、白桦和橡树类型通过建立森林实测参数与LAD之间的指数关系式模拟LAD随高度变化(图7(a)—(c))(Lalic和Mihailovic,2004),不考虑下层灌木和草被的影响,树冠层模拟值(实线)与观测值(十字点)趋势相似,呈现单峰分布。对于榉树类型,采用地基LiDAR数据基于VCP方法提取LAD曲线(Hosoi和Omasa,2007),结果显示树冠形态也为单峰分布,并在树冠中上层达到叶面积最大值。

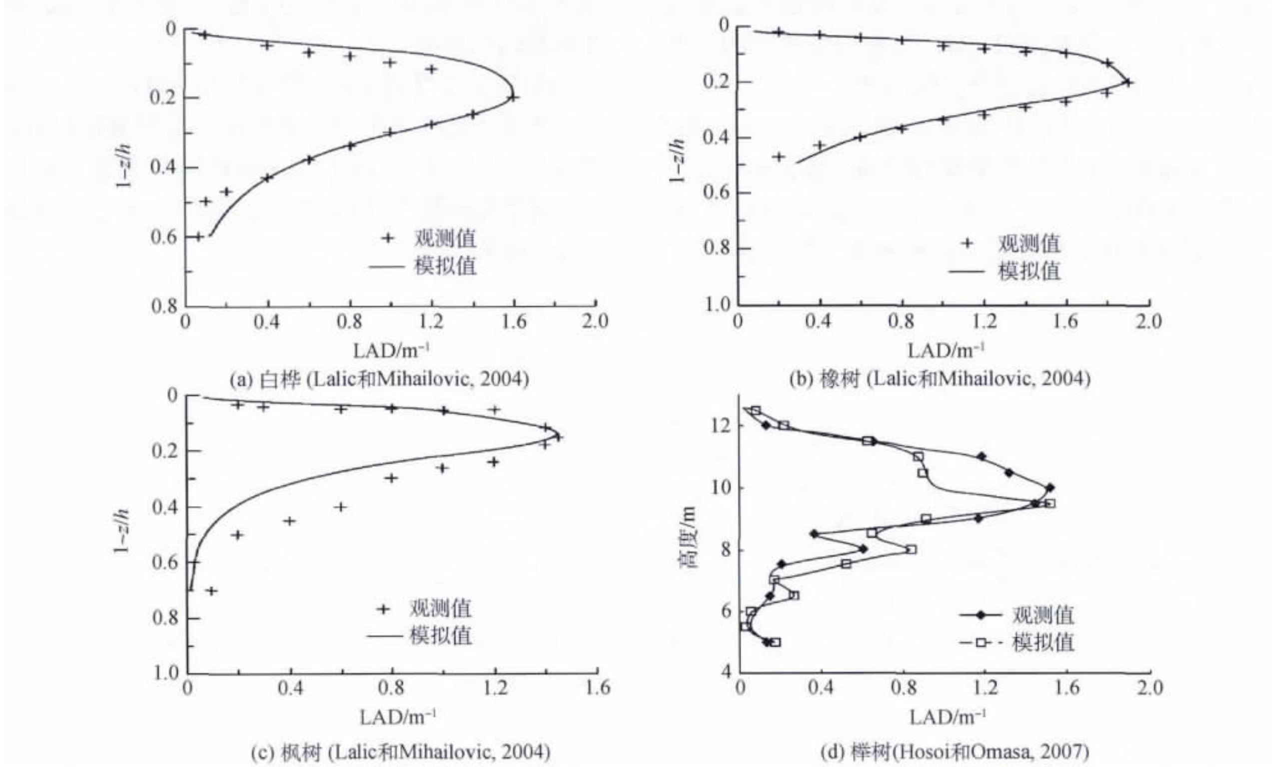



图7　几种典型阔叶林类型叶面积密度分布

## 6　结　论

目前,国内外开展了众多森林遥感监测的研究,基于微波遥感技术和主动激光雷达技术提取森林叶面积密度(LAD)曲线和冠层高度廓线(CHP)具有可行性,但是利用遥感提取森林垂直结构参数仍存在一些问题:

(1)提取的森林垂直结构参数范围较小、植被类型单一。遥感获取森林结构参数的主要手段包括野外实测和地基LiDAR定点观测数据及利用机载InSAR或LiDAR小区域观测数据。其中野外实测和地基LiDAR定点观测数据通常只能获取单一植被类型的LAD或CHP参数(Ross等,2000;Hosoi和Omasa,2006,2007),虽然机载LiDAR能够获取小区域森林群落冠层高度廓线(Lefsky和Harding,1999a,1999b),但获取的植被LAD和CHP曲线范围有限,并且所需的人力和物力成本比较高。

(2)缺乏成型的森林垂直结构参数产品。基于遥感技术提取森林垂直结构参数的研究仍处于探索阶段,各种研究方法都存在问题,因此没有提供成型的森林垂直结构参数产品。目前,主动激光雷达技术被认为是提取森林垂直结构参数的有效手段,并且已有一些LiDAR数据预处理与参数提取软件,如Tiffs和SLICER IMH处理系统,为森林垂直结构参数提取提供软件支持。

未来森林垂直结构参数提取需在数据源、提取算法两个方面继续深化研究:

(1)借助星载传感器数据提取森林垂直结构参数的研究比较少,目前只有星载的GLAS系统用于林业资源调查。随着星载激光雷达传感器技术的发展以及研究的不断深入,需要深入开展基于星载激光雷达系统提取森林垂直结构参数研究,拓宽提取森林垂直结构参数的空间范围。

(2)森林垂直结构不仅影响树冠层和树冠下植被的生长和分布,而且影响森林内部的电磁波辐射传输特性,因而需要深入理解森林内部结构和电磁波辐射传输机理,开展森林垂直结构定量描述和变

**化规律的研究,耦合多种遥感技术提取森林垂直结构参数。**

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